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Failure Pressure Prediction of Semi Spherical GFRP Shells in Thermal Environment

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KEYWORDS

Failure Pressure
GFRP
Pressure Vessel
Finite element
Temperature

ABSTRACT

In this article fluid-structure interaction of vibrating composite piezoelectric plates is investigated. Since the plate is assumed to be moderately thick, rotary inertia effects and transverse shear deformation effects are deliberated by applying exponential shear deformation theory. Fluid velocity potential is acquired using the Laplace equation, and fluid boundary conditions and wet dynamic modal functions of the plate are expanded in terms of finite Fourier series to satisfy compatibility along with the interface between plate and fluid. The electric potential is assumed to have a cosine distribution along the thickness of the plate in order to satisfy the Maxwell equation. After deriving the governing equations applying Hamilton's principle, the natural frequencies of the fluid-structure system with simply supported boundary conditions are computed using the Galerkin method. The model is compared to the available results in the literature, and consequently the effects of different variables such as depth of fluid, the width of fluid, plate thickness, and aspect ratio on natural frequencies and mode shapes are displayed.

1. Introduction

Composite pressure vessels have some advantages over metals namely, strength/weight ratio, resistance to chemical and so on. However, they have a few shortcomings with respect to metals that may result in the failure of composite vessels. The most important of all is the permeability of the composite pressure vessel when contains a high pressure gas such as air, oxygen, hydrogen, and helium. Factors such as pressure, temperature, humidity and type of fluid have pronounced effect on penetration of fluid molecules through the composite. Opening small hole through the composite thickness by fluid molecule results in a high speed of jet flow of contained fluid, consequently increase the damage up to vessel failure. Isotropic martials expand and/or contract as a result of pressure and temperature modification. Orthotropic materials such as polymer composites also have dimensional change as a result of pressure and temperature variations. There is a difference between metal and composite when they are exposed to the temperature variation, and that is residual stress developing in composite due to difference in the coefficient of thermal expansion between polymer and fibers.

Roy [1, 2] presented the strength analysis for multilayered spherical composite pressure vessels with quasi-isotropic layups based on the Tsai-Wu failure criterion. It is observed that thin shells failure occurs on the outside while thick shells failure occurs on the inside. Mouhamath et al. [3] inspected the burst pressure of spherical composite pressure vessels based on quadratic failure criterion considering material degradation factor. The burst pressure value is computed by theory when the failure probability becomes bigger than 0.9%. The theoretical values obtained bigger than those measured by experiment did. Mao et al. [4] examined the fracture strength of composite pressure vessels based on the statistical approach and extrapolation of the experimental burst test results. Kam [5] et al. explored first-ply failure strength of laminated composite pressure vessels applying both analytical and experimental methods.

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They revealed that the theoretical first-ply failure pressure results are very accurate for pressure vessels made of four or six plies, while for pressure vessels with eight plies the theoretical results become less sufficient.

Chang [6] reviewed the first-ply failure strength on angle-ply symmetric laminated composite pressure vessels subjected to uniform internal pressure is performed using an acoustic emission technique. They concluded that by increasing the loading rate, the applied stress increases and the burst of composite structure are highly controlled by viscoelastic properties of the matrix material. To increase life safety, Krishna et al. [13] proposed design of multilayered cylindrical composite pressure vessels using ASME analytical code and FEM. They indicated that stress and weight could be optimized by applying AlSiC composites.

Tomasz Czaplinski et al. Deolia and Shaikh [14, 15] presented a review study on burst pressure analysis of pressure vessels and reported ±45° fiber orientation angle as the optimum value to reach the maximum strength in composite pressure vessels. Balaji and Shivappa [16] applied FEM in order to compute burst pressure and burst failure locations for spherical pressure vessels. They indicated that doubling the thickness has doubled the burst pressure. Applying circumferential stiffeners, a negligible improvement in burst pressure is observed while using radial stiffeners can improve the burst pressure by 15%.

In the present study, the failure pressure of a composite spherical cap is computed applying experiment and FEM simulation. The hand layup process is used in a closed-mold to manufacture twelve test specimens. In order to compute the failure pressure, a computer-linked system is provided including pressure and temperature sensors. The experiment is operated using air to apply the internal pressure to the GFRP spherical cap specimens. A finite element model with S3R elements is produced applying ABAQUS commercial software, and the failure is contemplated to be controlled by strength. A comparison between FEM and experimental results is conducted, and good agreement is achieved. Tin order to examine the effect of thickness and stacking sequence on the failure pressure of the GFRP spherical cap in the thermal environment, parametric FEM studies have been Accomplished. A spherical cap, spherical dome, or spherical segment of a sphere is considered to be tested instead of sphere pressure vessel portrayed in Fig. 1. As indicated, the skirt is added to the spherical cap in order to hold or restraint the test specimen at the position in the apparatus during the pressure examining.

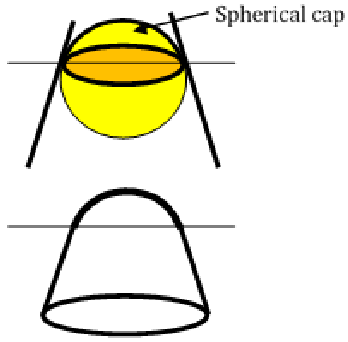


Fig. 1. Schematic presentation of the spherical cap with skirt

2. Experimental analysis

2.1. *Design of test specimen*

Any resin and fiber can be applied for the justification of the test process designed in the laboratory scale. The chosen materials for manufacturing of the test specimen were E-glass fiber with strength 200 MPa and ML-503 epoxy resin with HA-12 hardener. The GFRP test specimens contemplating [0/90/45/-45/90/0] arrangement are fabricated by the hand layup process by applying a special mold.

2.2. *Design & fabrication of the closed mold*

The special closed-mold is designed and fabricated as portrayed in Fig. 2. This mold consists of three parts of upper male, lower female, and a closing disk to manufacture the test specimen of GFRP. Fig. 3 (a & b) indicates how the composite is layed up on the male part and closed by the female part and disk.

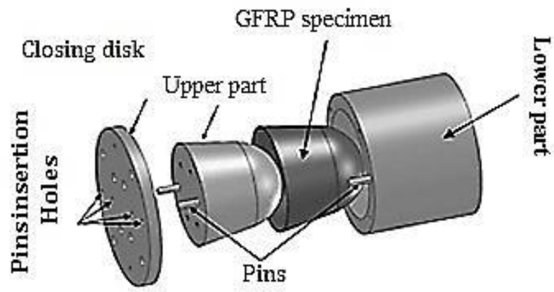


Fig. 2. Exploded view of the manufactured closed mold

(a) (b)

Fig. 3. (a): Male part of the mold, (b): closed mold

The composite test specimen was cured inside the closed mold at room temperature for eight hours. The cured specimen is illustrated in Fig. 4. As indicated, the cured specimen can be considered as two sections, the spherical cap, and the skirt. The base radius of the cap & thickness of specimens is measured 43.3 mm and 1mm, respectively.

In order to compute the laminate properties, four GFRP test specimens are burnt in Oven at 600°C for three hours in order to find the fiber volume fractions. An average of 37% volume fraction of fiber is determined, and the difference of volume fraction between the specimens was less than 2%. Closed tolerance of volume fraction indicates the quality design of the close mold. Knowing the properties of the fiber and resin and applying micromechanical rules with computed volume fraction, the elastic properties and strengths of GFRP lamina are obtained and presented in Table 1.

2.3. Design & fabrication of test apparatus

The apparatus for pressure examining the specimens at constant temperature has been designed and fabricated. It is possible control gas pressure up to 100 bars and temperature up to 150 Celsius. The apparatus, in general, is similar to the closed mold, except the top portion of male part is removed as presented in Fig. 5.

Fig. 4. A cured composite specimen

Table 1. Physical & mechanical properties of GFRP lamina.

GFRP properties	Value
E_1 (GPa)	34.255
E_2(GPa)	8.56
G_{12} (GPa)	2.724
υ_{12}	0.26
S_{11T} (MPa)	977.04
S_{11C} (MPa)	561.2
S_{22C} (MPa)	108.56
S12 (MPa)	66.24
α1 (10^{-6}/°C)	7.912
α2 (10^{-6}/°C)	0.203

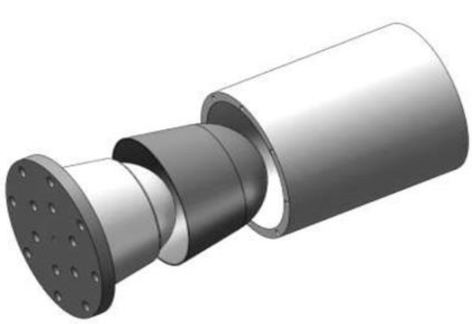


Fig. 5. Three parts test specimen holder

As portrayed in this figure, the spherical cap portion of the test specimen is not in contact with the male and female portion of the three-part holder. However, the skirt portion of the test specimen is griped by the male and female parts similar to the gripping of tensile examining specimens. This gripping beneficial in order to hold the test specimen in position while the spherical cap portion is pressurized from bottom. A schematic presentation of the setup is indicated in Fig. 6. The small volume between test specimen and male part is designed to ensure the security of testing during high pressure tests.

The inlet-outlet gas pressure from the bottom of the male part designed to better control the pressure inside the spherical cap. The volume between the spherical cap and the male part is designed to be very small in order to secure any damage during burst failure. A heating jacket is designed to heat the three-part holder from outside as well.

2.3.1. Specimen failure test

The main apparatus testing equipment's consist of three-part holder, air storage tank, pressure control system, temperature control system and a laptop.

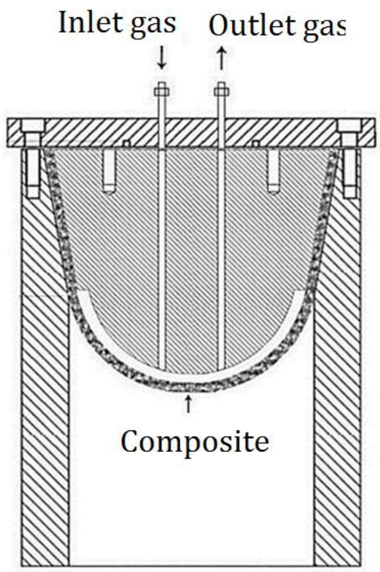


Fig. 6. Three parts test specimen holder

A thin layer of an impermeable material is sprayed on the inside surface of the test specimen in order to prevent air penetration in the composite while the pressure is increasing up to the failure of the specimens.

Applying an epoxy glue, the skirt portion of the GFRP specimen is sealed between the male and female parts of the holder. Subsequently, the specimen has been subjected to air pressure from bottom of the male part of the holder while the temperature on the spherical cap portion is kept constant as indicated in Fig. 6. The failure tests are operated constant temperatures 20°C, 40°C, 60°C and 80°C. The entire apparatus set up is portrayed in Fig. 7.

Output curves acquired from data collector sowing pressure vs elapse time. The maximum failure pressure at each temperature is extracted and listed in Table 2.

It is observed at the low temperature failure appearance was more like a small hole and pressure dropped gradually. At higher temperature a small crack appeared in the test specimen, and pressure dropped suddenly. This may be a result of softening of composite resin and there by having more resistance to matric cracking. Data extracted from all tests are plotted in pressure versus temperature coordinates as presented in Fig. 8. As can be observed, the failure of the spherical cap generally been reduced with increasing temperature. The failure mode should be matrix dominated since the fiber is not affected much in this temperature ranges.

3. Numerical analysis

3.1. FEM modelling

The finite element model of the spherical cap is produced applying S3R elements in ABAQUS commercial software, as depicted in Fig. 9. The boundary condition is selected according to the three-part holder shown in Fig. 6. The outward displacement of the edge of the spherical cap is fixed, and the failure analysis is demonstrated based on Hashin's failure criterion. A hydrostatic internal pressure used as loading.

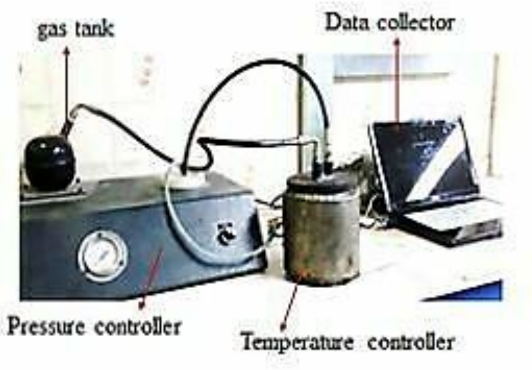


Fig. 7. Designed apparatus for pressure failure testing.

Table 2. failure pressure at various temperatures

Temperature (°C)	Pressure (Bar)
20	8.9
40	8.2
60	7.8
80	5.9

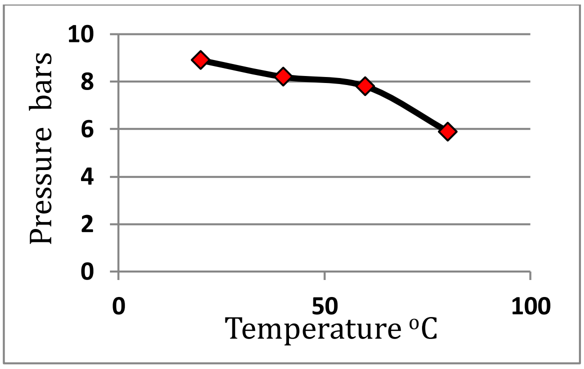
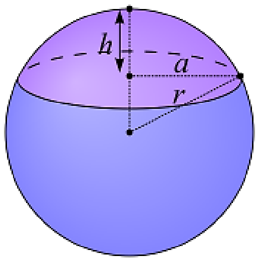


Fig. 8. Experimental failure pressure-temperature curve.



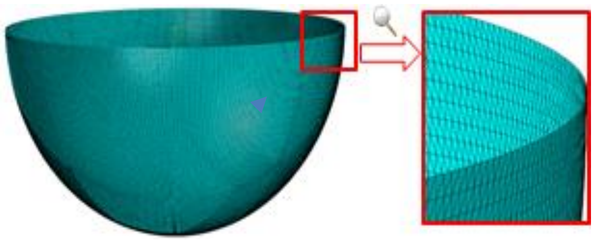


Fig. 9. Meshed finite element model using S3R elements

The semi spherical GFRP shell radius is computed applying height and base radius of spherical cap. For $r = \frac{a^2-h^2}{2h} = 43.35$ mm, $\frac{t}{r} = 0.023$.

3.2. Effect of thickness

The FEM calculation of the failure pressure is presented in Fig. 10 considering different t/r ratios and [0/90/45/-45/90/0] arrangement for the test specimens. As the t/r ration increase, the failure pressure also increases. Despite that, temperature has a reversed effect where the failure pressure decreases as the temperature increase.

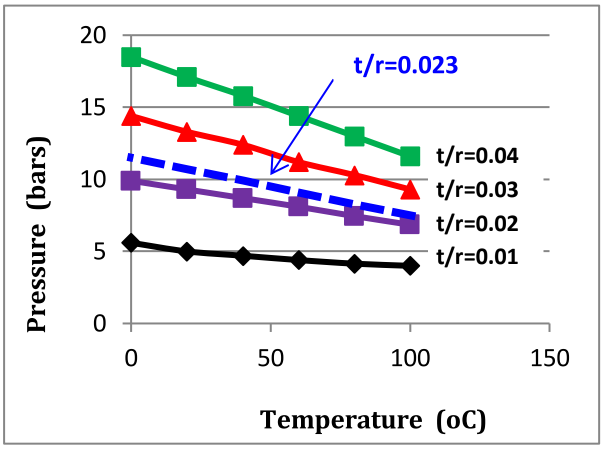


Fig. 10. FEM failure pressure at various t/r ratios

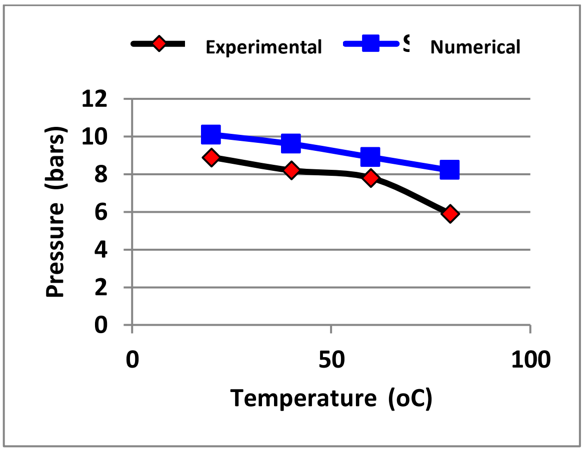


Fig. 11. Experimental and FEM results for failure pressure

For comparison of the numerical calculation with the experimental results, the failure curve for the t/r ratio of tested specimens is needed. Pursuant to the calculation the thickness-radius ratio is t/r=0.023 for the tested specimens. By interpolating between two curves of t/r=0.02 and t/r=0.03, the numerical result of the failure curve for the test specimen is acquired as presented with black color in Fig. 9.

4. Verification

The FEM results are verified by the experimental results as shown in Fig. 11. In both cases it is indicated the failure pressure is decreasing with temperature increase. because the reason behind this can be the strength of the composite is decreased by temperature increasing. The curve calculated from the numerical calculation is linear and continuously decreasing with the temperature. However, the curve obtained from the experimental result is not changing linearly. At last, the failure pressures obtained from experimental results are always less than failure pressures computed from numerical method. Two major reasons may be noted for these differences.

Firstly, they may be as a result of physical and mechanical parameters that are not contemplated in finite element formulation. Moreover, error may be coming from experimental set up and design deficiency.

5. Conclusions

An effort is made to design a process in a laboratory scale to test small spherical composite cap to predict the failure pressure of spherical GFRP pressure vessel in thermal environment. The designed test specimens manufactured by closed mold have closed geometric tolerance and fiber volume fraction. This means a good quality design of the closed mold.

The specimens examined in the designed apparatus under control pressure & temperature. Tolerance for the pressure is ±0.5 bar and for the temperature±1°C. Best sealing obtained in three the peace holder keeping pressure up to 100 Bars.

The failure pressure obtained from the experimental test of GFRP test specimens with [0/90/45/-45/90/0] arrangement is compared with the results calculated by FEM. The average difference of the failure pressure for the GFRP test samples calculated to be 16.5%. This difference is reasonable enough to trust the laboratory process testing for prediction of the failure pressure of composite pressure vessels.

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